6 Resource Allocation in OFDM-Based WiMAX

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CONTENTS

The worldwide interoperability for microwave access (WiMAX) extends the transmission rate and range of wireless communications beyond the limits of existing technologies while allowing for heterogeneous traffic transmissions. To achieve all these goals, qualified protocols for WiMAX should effectively utilize the spectrum and overcome the deficits of wireless channel while maintaining a satisfactory level of heterogeneous services for users. WiMAX supports air interfaces based on orthogonal frequency division multiplexing (OFDM) which is a robust and flexible technique for transmissions and resource allocations, respectively, over wireless channel. The basic characteristics of OFDM that mitigate the wireless channel impairments are stated in this chapter. Moreover, several resource allocation schemes for subcarrier and power allocation problem in OFDM-based networks are surveyed that provides a deep insight into the problem. Besides, a resource allocation scheme for WiMAX is presented that considers the heterogeneous requirements of WiMAX users and the utilization of scarce resources simultaneously.

6.1 INTRODUCTION

WiMAX is expected to provide high data-rate services over a service area as large as a metropolitan area network. Broad spectrum and large coverage area usually cause severe interference and multipath transmissions, unless an appropriate design takes effect. WiMAX deploys multicarrier transmission based on the OFDM and multiple access based on the orthogonal frequency division multiple access (OFDMA). OFDM mitigates noise, multipath, and interference effects which are the main challenges of wireless communications. OFDMA is very flexible in allocating resources which are very critical for wireless networks.

The main scarce resources in wireless networks are spectrum and power. In spite of the large frequency band of the broadband networks, network designers allocate it very efficiently to serve as many satisfied users as possible while maintaining reasonable level of revenue for service providers. Mobile and portable devices are required to consume minimal power to extend their battery lifetime. Furthermore, fixed equipment and base stations (BSs) are expected to consume as low power as possible due to the health and global energy concerns. The resource constraints of the wireless medium become more critical when resource demanding applications are dealt with. According to the IEEE 802.16 standard [1], the coexistence of real-time and non-real-time traffic in WiMAX is promising. Therefore, existing resource allocation schemes that support one type of the traffics fails and the development of new schemes that simultaneously satisfy diverse quality-of-service (QoS) demands of the heterogeneous traffic and fairly manage resources becomes necessary.

This chapter focuses on the resource allocation in OFDM-based WiMAX networks. We investigate how the flexibility and granularity of OFDM can be incorporated in a resource allocation scheme to improve network performance and resources utilization. We review the OFDM spectrum and power allocation schemes for centralized and decentralized networks, respectively. In a centralized infrastructure, a central station known as BS, allocates the resources to users based on either perfect or imperfect channel states information (CSI). In a decentralized infrastructure, users compete or coordinate to capture the resources; BS does not exist or has a minimal role in the network management. Since centralized schemes have a slightly classical form, we present a general model for the resource allocation problem and some proposed solutions. The limitations of each problem are discussed and a problem formulation that conforms the diverse QoS requirements of WiMAX is described. Unlike the centralized schemes, decentralized schemes are quiet different in implementation, so we briefly review some of the proposed schemes and discuss their specifications. Some of the reviewed schemes in this chapter have not been essentially designed for WiMAX. However, reviewing them will give a deep insight of the challenges of the OFDM resource allocation in WiMAX. Besides, these can be considered in some specific applications of WiMAX, e.g., delay tolerant networks.

The remainder of this chapter is organized as follows. We present the details of the wireless channel and the OFDM transceiver in Section 6.2. First, the wireless radio channel impairments and the basics of OFDM and OFDMA are explained. Then, the MAC sublayer of the IEEE 802.16 standard [1] is briefly described. Sections 6.3 and 6.4 are devoted to reviewing the resource allocation schemes for centralized and decentralized networks, respectively. Open research issues are stated in Section 6.5. The chapter is concluded in Section 6.6.

6.2 OFDM-BASED WiMAX

The channel impairments significantly degrade the performance of a broadband wireless communication network. Multicarrier transmission is selected as a promising technique for future communication due to its robustness against the frequency selectivity of broadband communications [2].

In this section, we explain the fading channels characteristics and how OFDM can improve communications over fading channels. An overview of the OFDM and OFDMA transceivers structures along with a detailed discussion of their operations is presented. In addition, the required knowledge of PHY and MAC relevant to the resource allocation problem formulation is described such as the relation among transmission rate, power, channel gain, and bit error probability. In this chapter, MAC specification of WiMAX is based on the IEEE 802.16 standard.

6.2.1 RADIO CHANNEL

The wireless propagation channel constrains the information communication capacity between a transmitter and a receiver. The design of a wireless communication system's coding, modulation, signal-processing algorithms, and multiple access scheme is predicated on the channel model. The wireless channel is also generally time-varying, space-varying, frequency-varying, polarization-varying, dependent on the particular environment and the transmitter and receiver's location. Each type of variation presents randomness and unpredictability. Nevertheless, the communication channel modeling has been well established to characterize the channel by various time and frequency metrics [3].

A channel's impulse response to $\delta(\tau)$, Dirac impulse function transmitted at the moment τ, looks like a series of impulses, because of the multipath reflections, represented by a time-variant function [4]

$$h(\tau, t) = \sum_{p=0}^{Np-1} a_p(t) e^{j(2\pi f_{D,p} t + \varphi_p)} \delta(\tau - \tau_p(t)). \tag{6.1}$$

$a_p, f_{D,p}, \varphi_p$, and τ_p, respectively refer to the pth multipath's complex-valued arrival amplitude, Doppler frequency, phase, and arrival excess delay, i.e., the delay measured with respect to the arrival of the first multipath component. N_p symbolizes the number of multipaths whose amplitudes exceed the detection threshold. In practice, the number of multipath components that can be distinguished is very large. Therefore, only those multipaths that are temporally resolvable, i.e., their difference in arrival time to the receiver is greater than the inverse of the input signal bandwidth, are considered in detection.

The multipath propagation mechanisms (reflection, diffraction, and scattering) result in delay dispersion, which corresponds to frequency selectivity in the spectral domain. Each multipath power and delay is given by the power delay profile (PDP) denoted by $|h(\tau)|^2$, where $h(\tau)$ denotes the temporally stationary discrete-time channel's impulse response:

$$h(\tau) = \sum_{p=0}^{Np-1} a_p \delta\left(\tau - \tau_p\right). \tag{6.2}$$

The channel's PDP is a mathematical function whose complete characterization necessitates a long signal. However, the scalar metrics mean delay

$$\bar{\tau} = \frac{\int_0^\infty |h(t)|^2 t \mathrm{d}t}{\int_0^\infty |h(t)|^2 \mathrm{d}t} = \frac{\sum_{p=0}^{Np-1} \left|a_p\right|^2 \tau_p}{\sum_{p=0}^{Np-1} \left|a_p\right|^2} \tag{6.3}$$

and RMS delay spread

$$\tau_{\mathrm{RMS}} = \frac{\int_0^\infty |h(t)\,(t - \bar{\tau})|^2 \mathrm{d}t}{\int_0^\infty |h(t)|^2 \mathrm{d}t} = \frac{\sum_{p=0}^{Np-1} \left|a_p\left(\tau_p - \bar{\tau}\right)\right|^2}{\sum_{p=0}^{Np-1} \left|a_p\right|^2} \tag{6.4}$$

characterize the PDP temporal dispersion [5]. Figure 6.1a shows the graphical representations of the mean delay and RMS delay spread. When the channel delay dispersion is greater than the signal reciprocal bandwidth, i.e., the symbol duration $T_s \ll \tau_{\mathrm{RMS}}$, the transmitted train of symbols overlaps at the receiver. This phenomenon is known as inter-symbol interference (ISI) [6] which is illustrated in Figure 6.1a.

Whereas the preceding metrics are in the relative-delay domain, channel fading may also be characterized in the spectral domain. Specifically, the coherence bandwidth, B_c, offers an alternative metric to the RMS-delay-spread, τ_{RMS}, to measure the channel's delay dispersion. The channel impulse response's Fourier transform gives the time-variant channel transfer function [4]:

$$H(f, t) = \sum_{p=0}^{Np-1} a_p(t) e^{j(2\pi(f_{D,p} t - f \tau_p(t)) + \varphi_p)}. \tag{6.5}$$

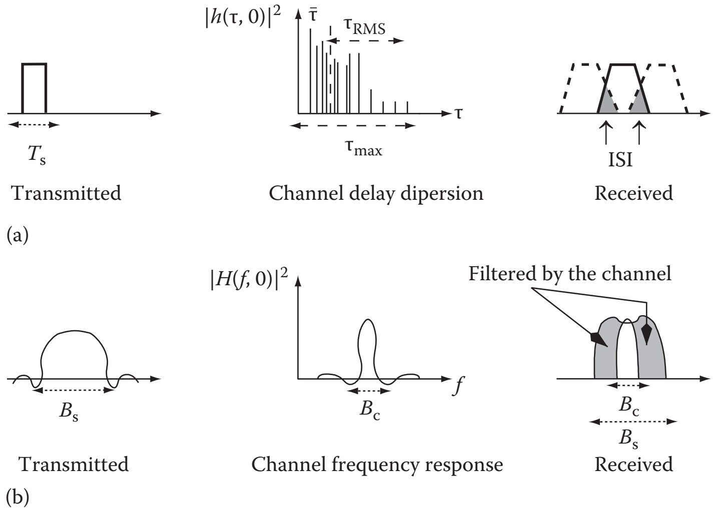

FIGURE 6.1 Wireless channel effect: (a) delay dispersion (b) frequency selectivity.

We define the channel frequency response's autocorrelation function as [7]

$$R(\Delta f) = E\{H(f,0)H^*(f - \Delta f, 0)\} \tag{6.6}$$

where $(\cdot)^*$ denotes the complex conjugate. The coherence bandwidth B_c measures the spectral width of $|R(\Delta f)|$ over which the channel is considered frequency flat. Note that the frequency selectivity is relative to the transmitted signal bandwidth. In particular, if the channel's B_c is less than the transmitted signal bandwidth, the channel distorts the received signal at selected frequencies as shown in Figure 6.1b. On the other hand, the channel does not affect the received signal, if its B_c is greater than the transmitted signal bandwidth.

Independently from delay dispersion and frequency selectivity, user mobility causes frequency dispersion which in turn results in channel time selectivity. The time correlation function [7,8]

$$R(\Delta t) = E\{H(0,t)H^*(0, t - \Delta t)\} \tag{6.7}$$

quantifies the time-varying nature of the channel. From $R(\Delta t)$, the channel coherence time T_c can be obtained, and it is defined as the time duration over which the channel is essentially flat [4]. $R(\Delta t)$ Fourier transform is the channel Doppler power spectrum that its correlation width is the Doppler
AQ1 spread B_d. If the channel impulse response changes rapidly within the symbol duration, i.e., $T_c < T_s$, the transmitted signal undergoes fast fading which leads to signal distortion [6], or the Doppler spread B_d is greater than the transmitted signal bandwidth. This effect induces frequency offset and possibly inter-carrier interference (ICI) in dense spectrums. In summary,

- Delay dispersion results in frequency selective fading that alters the received signal waveform and hence causes performance degradation. The channel effect can be avoided by transforming the broadband signal into parallel narrowband signals with bandwidth smaller than the channel's B_c.
- Frequency dispersion smears the signal spectrum in the frequency domain. It causes time selectivity that varies the signal at a rate higher than the rate at which the channel can be accurately estimated.

6.2.2 An Overview of OFDM

Frequency division multiplexing (FDM) appeared in 1950s [2]; however, its implementation required multiple analog radio frequency (RF) modules in each transceiver that made FDM impractical [8]. Recently, the implementation of IFFT/FFT and FDM ability in mitigating the channels ISI brought FDM back under light. While FDM major advantage is eliminating the ISI effect, it does not eliminate the ICI that rises due to closely packed multicarriers. Alternatively, data symbols can be modulated on orthogonal multiple carriers to reduce ICI, which is termed OFDM [9]. AQ2

The high data-rate stream is partitioned into B data blocks of N_{sc} length at the transmitter. The symbols are serial-to-parallel converted which increases the source symbol duration T_{s} to

$$T'_{\text{s}} = N_{\text{sc}} T_{\text{s}}. \tag{6.8}$$

As the symbol duration increases, the ISI effect significantly decreases (Section 6.2.1). Thus, the need for an equalizer at the receiver is eliminated, which reduces the complexity of the receiver. After serial-to-parallel conversion, block b represents the OFDM symbol which consists of N_{sc} complex data symbols denoted by $\{s_n, b\}$, $n = 0, \ldots, N_{\text{sc}} - 1$, $b = 1, \ldots, B$. For simplicity, the bth index is dropped and we only refer to the s_n, $n = 0, \ldots, N_{\text{sc}} - 1$ sequence in each block, i.e., the OFDM symbol, unless it is necessary. Figure 6.2 depicts a typical multiuser OFDM/OFDMA transmitter and receiver block diagram. OFDM is implemented by applying inverse discrete Fourier transform (IDFT) to the data sequence s_n which gives the following samples x_v, $v = 0, \ldots, N_{\text{sc}} - 1$, of each OFDM symbol [4]:

$$x_v = \frac{1}{N_{\text{sc}}} \sum_{n=0}^{N_{\text{sc}}-1} s_n e^{j\frac{2\pi nv}{N_{\text{sc}}}} \qquad v = 0, \ldots, N_{\text{sc}} - 1. \tag{6.9}$$

Whereas serial-to-parallel conversion only reduces the ISI effect, cyclic extension of the symbol by inserting a guard interval T_{g} that is longer than the maximum channel dispersion time $\tau_{\max}$ eliminates the residual ISI effect [4]. The guard interval is a copy of T'_{s} last $L_{\text{g}} = \left\lceil \frac{\tau_{\max} N_{\text{sc}}}{T'_{\text{s}}} \right\rceil$ samples (practically, the symbol source is continuous and guard insertion is archived by adjusting the starting phase and making the symbol period longer [10]). After cyclic extension of the OFDM symbol, the time domain sampled sequence becomes

$$x'_v = \frac{1}{N_{\text{sc}}} \sum_{n=0}^{N_{\text{sc}}-1} S_n e^{j\frac{2\pi nv}{N_{\text{sc}}}} \qquad v = -L_{\text{g}}, \ldots, N_{\text{sc}} - 1. \tag{6.10}$$

Then, the sequence x' is passed through digital-to-analog converter, and its output is transmitted through the wireless channel. Figure 6.3 depicts the time and frequency representation of an OFDM frame.

By implementing the OFDM multicarrier modulation, the continuous channel transfer function (Equation 6.5) is sampled in time at the OFDM symbol rate $1/T''_{\text{s}}$ and in frequency at spacing F_{s}. The discrete channel transfer function adapted to multicarrier signals is given by [4]

$$\begin{aligned} H_{n,i} &= H(nF_{\text{s}}, iT''_{\text{s}}) \\ &= \sum_{p=0}^{N_p-1} a_p(t) e^{j(2\pi(f_{D,p} iT''_s - nF_s \tau_p(t)) + \varphi_p)} \\ &= a_{n,i} e^{j\varphi_{n,i}}. \end{aligned} \tag{6.11}$$

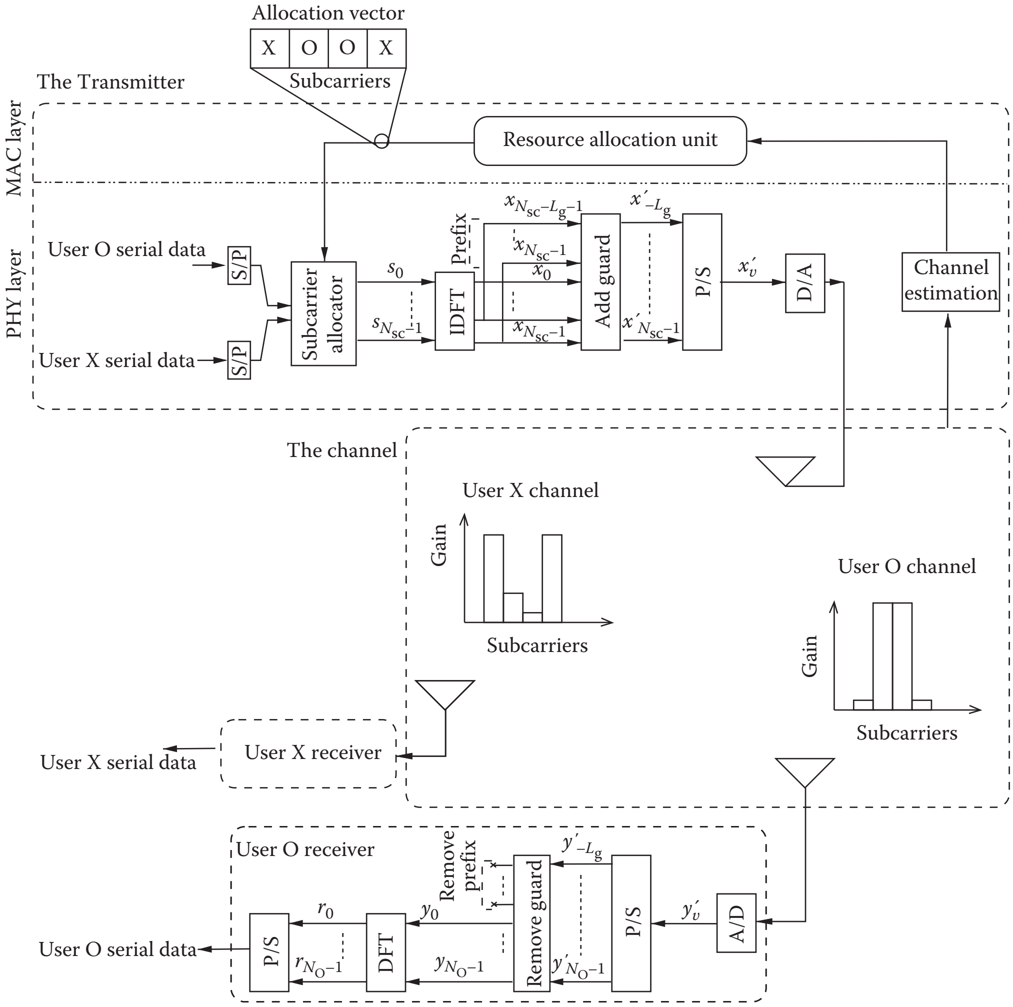

FIGURE 6.2 OFDMA transmitter and receiver's PHY and MAC structure.

A transmitted symbol on subcarrier j of the OFDM symbol b is multiplied by the resulting fading amplitude $a_{n,b}$ and rotated by random phase $\varphi_{n,i}$. The subcarrier gains can be represented by the following $N_{sc} \times N_{sc}$ channel matrix for the OFDM symbol i

$$\mathbf{H} = \left[H_{0,0}\ H_{1,1}\ \ldots\ H_{N_{sc}-1,N_{sc}-1}\right] \times \mathbf{I}, \tag{6.12}$$

where $\mathbf{I}$ is the identity matrix. The OFDM symbol index i has been dropped for simplicity. Let h_v be the sampled L sequence of the channel impulse response $h(\tau, t)$ given in Equation 6.1 at a particular time instant t, i.e., $h_v = h(lT_s'', bT_s'')$, $l = 0, \ldots, L = (\tau_{max}/T_s''))$, and represented by the vector $\mathbf{h}$. Then, the matrix $\mathbf{H}$ diagonal elements are the discrete Fourier transform (DFT) of channel discrete impulse response.

After analog-to-digital conversion at the receiver, the received sampled sequence y_v', $v = -L_g, \ldots, N_{sc} - 1$ contains ISI in the first L_g samples that are discarded. The remaining sequence $0, \ldots, N_{sc} - 1$ is demodulated by the DFT. The DFT demodulated multicarrier sequence r_n, $n = 0, \ldots, N_{sc} - 1$, consists of N_{sc} complex valued symbols [4]:

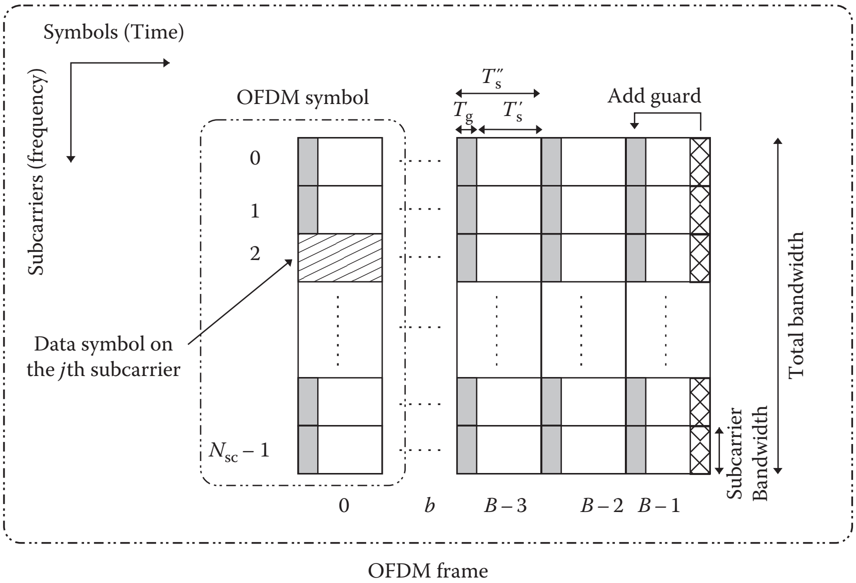

FIGURE 6.3 Time and frequency representation of an OFDM frame.

$$r_n = \sum_{n=0}^{N_{sc}-1} y_v e^{-j\frac{2\pi nv}{N_{sc}}}, \quad n = -0, \ldots, N_{sc} - 1. \tag{6.13}$$

Since x_v and y_v are the sampled sequences of the transmitted and received signals, respectively, the vector representation of the received data symbols is given by

$$\begin{aligned} \mathbf{r} &= \left[r_0\ r_1 \ldots r_{N_{sc}-1}\right]^{\mathrm{T}} \\ &= \mathbf{W}^{\mathrm{H}}\mathbf{y}. \end{aligned} \tag{6.14}$$

The operator $(\cdot)^{\mathrm{H}}$ denotes the matrix Hermitian, $\mathbf{y}$ is defined as $\left[y_0\ y_1 \ldots y_{N_{sc}-1}\right]^{\mathrm{T}}$, and $\mathbf{W}$ is the $N_{sc} \times N_{sc}$ IDFT matrix. The received signal in the frequency domain cannot be represented by the multiplication of the transmitted and the channel frequency domain representation because y_v is related to x_v and h_v by linear convolution rather than circular convolution [8]. However, the cyclic convolution is created for OFDM by appending the L_g samples $(x_{N_{sc}-L_g-1}, x_{N_{sc}-L_g}, \ldots, x_{N_{sc}-1})$ to the sequence x_v. This circular convolution of the two periodic sequences is transformed into the product of their DFTs [8]:

$$r_n = H_n s_n \quad n = 0, \ldots, N_{sc} - 1 \tag{6.15}$$

which can be alternatively written as

$$\mathbf{r} = \mathbf{Hs}. \tag{6.16}$$

r and **s**, respectively, are the received symbols and transmitted symbols matrix representation. Ignoring the additive noise effect and substituting Equation 6.14 in the left-hand-side of Equation 6.16 result in

$$\begin{aligned} \mathbf{W}^{\mathrm{H}}\mathbf{y}^{\mathrm{T}} &= \mathbf{Hs} \\ \mathbf{H}^{-1}\mathbf{W}^{\mathrm{H}}\mathbf{y}^{\mathrm{T}} &= \mathbf{s}, \end{aligned} \tag{6.17}$$

where $\mathbf{H}^{-1}$ is the matrix inverse (the inverse of a diagonal matrix is a matrix with diagonal elements $\frac{1}{H_{n,n}}$ $n = 0, \ldots, N_{sc} - 1$). Therefore, based on the availability of the channel estimation matrix **H** and by the implementation of DFT, the transmitted symbols can simply be recovered [11].

6.2.3 Transmission Rate

Multicarrier modulation transforms a wide band channel experiencing selective fading onto multiple bands that experience flat fading. The flat fading channel is assumed to be static over the OFDM symbol duration. In addition, a perfect CSI is assumed to be available at the transmitter. Under these assumptions, the normalized transmission rate (bits/seconds/hertz) on the *j*th subcarrier is given by [12]

$$r_j = \log_2\left(1 + p_j \frac{|H_j|^2}{N_0}\right), \tag{6.18}$$

where p_j, $|H_j|^2$, and N_0, respectively are, the allocated power, the channel gain, and the AWGN noise variance. The Shannon capacity in Equation 6.18 is an upper bound that asymptotically approaches the transmission rate over wireless channels. Nevertheless, this upper bound is hard to achieve in practice especially in the network under consideration where adaptive modulation and coding (AMC) is adopted. Particularly, WiMAX [1] supports the adaptive constellation size change of M-OAM and M-PSK following the channel gains changes. From a resource allocation perspective, given the required P_b and channel gains, the allocated power p_j and transmission rate $r_j = \log_2 M$, where M denotes the modulation level, can be adapted. This adaptation is performed by inverting the modulation schemes' P_b approximation functions. The exact approximations of the M-QAM and M-PSK P_b, respectively are, given by [13]

$$P_b \approx \frac{4}{\log_2 M} Q\left(\sqrt{\frac{3p_j \frac{|H_j|^2}{N_0} \log_2 M}{M-1}}\right) \tag{6.19}$$

$$P_b \approx \frac{2}{\log_2 M} Q\left(\sqrt{2p_j \frac{|H_j|^2}{N_0} \log_2 M} \sin\left(\frac{\pi}{M}\right)\right). \tag{6.20}$$

In Refs. [14–16] Equations 6.19 and 6.20 are inverted to obtain the constellation size and power adaptation for a specific P_b. However, the $Q(\cdot)$ function cannot be easily inverted in practice, because numerical inversions are necessary [13]. Alternatively, the exact approximation can be written in a form that is easy to invert [17–20]. Because both modulation schemes are special cases of the M-ary modulation techniques [21], Equations 6.19 and 6.20 can be written as

$$P_b \approx c_1 \exp\left[\frac{-c_2 p_j \frac{|H_j|^2}{N_0}}{2^{c_3 r_j} - c_4}\right], \tag{6.21}$$

where $c_1 = 0.2$, $c_2 = 1.5$, $c_3 = 1$, and $c_4 = 1$ for M-QAM and $c_1 = 0.05$, $c_2 = 6$, $c_3 = 1.9$, and $c_4 = 1$ for M-QPSK [13]. By assuming "=" instead of "≈" in Equation 6.21 and solving for M, we obtain

$$M = \sqrt[c_3]{\left(\frac{c_2}{-\ln(\frac{P_b}{c_1})} P_j \frac{|H_j|^2}{N_0} + c_4\right)} \tag{6.22}$$

The adaptive modulation transmission rate as a function of P_b can be obtained by substituting Equation 6.22 in $r_j = \log_2 M$:

$$r_j = \frac{1}{c_3} \log_2 \left(c_4 + \frac{c_2}{-\ln\left(\frac{P_b}{c_1}\right)} P_j \frac{|H_j|^2}{N_0} \right). \tag{6.23}$$

Note that the transmission rates Equations 6.23 and 6.18 are similar. Thus, a resource allocation scheme that maximizes one of them maximizes the other [23]. This result broadens the applicability of resource allocation schemes to networks that adopt different modulation schemes.

6.2.4 MAC Sublayer

Resource allocation is one of the major tasks of MAC because the medium access mechanisms of MAC directly affect the spectrum and power utilization. Accordingly, the MAC sublayer specifications in the IEEE 802.16 standard, relevant to our discussion in the next section, are introduced in the following.

Despite the advantages of OFDM in mitigating the channels's impairments as mentioned before, underutilization of transmitter power and network subcarriers is its disadvantage. When an OFDM transmitter accesses the channel in a time division manner, e.g., time division multiple access (TDMA), the transmitter is forced to transmit on all available subcarriers N_{sc}, although it may require a less number of subcarriers to satisfy its transmission rate requirement. Consequently, the transmitter power consumption increases as the number of subcarriers increases. This disadvantage motivates the development of a PHY technology where transmitters are multiplexed in time and frequency, i.e., OFDMA. In such a technology, the users are exclusively assigned a subset of the network available subcarriers in each time slot [8,24]. The number of both time slots and subcarriers can be dynamically assigned to each user; this is referred to as dynamic subcarrier assignment (DSA) which introduces multiuser diversity. The multiuser diversity gain arises from the fact that the utilization of given resources varies from one user to another. A subcarrier may be in deep fading for one user (e.g., the second subcarrier for user X in Figure 6.2) while it is not for another user (e.g., the same subcarrier for user O). Allocating this particular subcarrier to the user with higher channel gain permits higher transmission rate. To achieve multiuser diversity gain, a scheduler at the MAC sublayer is required to schedule users in appropriate frequency and time slots.

Point-to-multipoint (PMP) as well as mesh topologies are supported in the IEEE 802.16 standard. PMP mode operations are centrally controlled by the BS, but mesh mode can be either centralized or decentralized, i.e., distributed. In a centralized mesh, a mesh BS (a node that is directly connected to the backbone) coordinates communications among the nodes. Decentralized mesh is similar to multihop adhoc networks in the sense that the nodes should coordinate among themselves to avoid collision or reduce the transmission interference.

In PMP mode, the uplink (UL) channel, transmissions from users to BS, is shared by all users, i.e., UL is a multiple access channel. On the other hand, downlink (DL) channel, transmissions from BS to subscriber stations (SSs), is a broadcast channel. The duplexing methods of UL and DL include time division duplexing (TDD), frequency division duplexing (FDD), and half-duplex FDD (HFDD). Unlike PMP mode, there is no clear UL and DL channel defined for mesh mode.

An outstanding feature of WiMAX is heterogeneous traffic support over wireless channels. IEEE 802.16 provides service for four traffic types known as service flows. The mechanism of bandwidth assignment to each SS depends on the QoS requirements of its service flows. The service flows and their corresponding bandwidth request mechanisms are as follows:

- Unsolicited grant service (UGS): This service supports constant bit rate traffic. Bandwidth is granted to this service periodically or in case of traffic presence by the BS.
- Real-time polling service (rtPS): This service has been provided for real-time service flows with variable-size data packets issued periodically. rtPS flows can send their bandwidth request to the BS after being polled.
- Non-real-time polling service (nrtPS): This service is for non-real-time traffic with variable-size data packets. nrtPS can gain access to the channel using monocast or multicast polling mechanisms. Upon receiving a multicast polling, the nrtPS service can take part in a contention in the bandwidth contention range.
- Best effort (BE) service: This service provides the minimum required QoS for non-real-time traffic. The channel access mechanism of this service is based on contention.

6.3 CENTRALIZED SUBCARRIER AND POWER ALLOCATION SCHEMES

In a network with a centralized resource allocation scheme, the BS allocates OFDM subcarriers and power to the users in both UL and DL based on the perfect knowledge of CSI. The users estimate the CSI and report it to the BS at the beginning of each MAC frame interval. It is assumed that the estimation error is negligible and the CSI remains constant during the next frame duration [25]. The BS assigns the resources, subcarrier, and power based on the CSI and broadcast the allocation vector on a signaling channel at the beginning of the next MAC frame transmission. The main difference between UL and DL resource allocation is the power limitation. In DL, the maximum allocated power is limited by the BS power, P_{BS}. However, in UL allocated power to the subcarriers of each user is limited by the user's device transmission power which is assumed to be totally devoted to transmission unless it causes an unacceptable interference among neighbors. In this section, first, we present a general resource allocation model for DL. Then, we discuss how the model changes for a different objective of the resource allocation problem. Finally, we present the subcarrier and power allocation model for UL.

6.3.1 PROBLEM FORMULATION

DL resource allocation is usually modeled as an optimization problem whose objective function and constraints are determined based on the users' requirements and network specifications. Depending on the definition of the objective functions, different utilization performance are expected. Resource allocation algorithms are available in the literature focus on two general objectives; either data rate maximization or power minimization subject to constraints based on the network model. Using a general objective function of rate, $F(r)$, we present a model for the subcarrier and power allocation optimization problem constrained by the BS maximum power. The problem formulation of power minimization in DL are not discussed here. Interested users are referred to Refs. [16,26].

Mixed integer nonlinear programming (MINLP) model is appropriate where a discrete network structure and continuous parameters are simultaneously formulated [27]. In DL, the subcarrier and power allocation problem is usually addressed as an MINLP optimization problem. The feasible region of the MINLP model contains integer variables representing subcarriers allocated to the users and continuous variables representing the power allocated to the subcarriers. The network parameters used in the optimization model are given in Table 6.1.

To show the subcarrier assignment to user i, a $K \times 1$-vector c_i of binary variables, called the subcarrier allocation vector of user ith, is defined with elements as follows:

$$c_{ij} = \begin{cases} 1 & \text{if } j\text{th subcarrier is assigned to } i\text{th user} \\ 0 & \text{otherwise.} \end{cases} \quad (6.24)$$

Each user can be allocated several subcarriers, but each subcarrier is exclusively allocated to one user. A subcarrier may not be assigned to any user due to its severe channel gain. This constraint is mathematically shown by

TABLE 6.1
Notions Description

Notion	Description
U	Total number of users in the network
K	Total number of the OFDM subcarriers in the network
$\mathcal{K} := \{1, 2, ..., K\}$	The set of subcarriers
$\mathcal{U} := \{1, 2, ..., U\}$	The set of users
i	ith user
j	jth subcarrier
$\lvert H_{ij}\rvert^2$	The channel gain of the ith user on the jth subcarrier
N_0	AWGN noise variance
p_{ij}	Allocated power to the ith user on the jth subcarrier
r_{ij}	Allocated rate to the ith user on the jth subcarrier
P_{BS}	BS total power budget
$R^i_{\min}$	Minimum service rate requirement of the ith user

$$\sum_{i=1}^{U} c_{ij} \leq 1 \quad \forall j \in \mathcal{K}. \tag{6.25}$$

If the jth subcarrier is not assigned to the ith user, the allocated power to the ith user on the jth subcarrier must be zero. Therefore, for every user $i = 1, \ldots, U$ and every subcarrier $j = 1, \ldots, K$, we must have

$$\text{If } c_{ij} = 0 \text{ then } p_{ij} = 0. \tag{6.26}$$

We include this restriction in the model through the following Equation:

$$p_{ij} \leq P_{BS} c_{ij} \ \ \forall i \in \mathcal{U}, \ \forall j \in \mathcal{K}. \tag{6.27}$$

Note that, if $c_{ij} = 0$, the Equation 6.27 implies $p_{ij} \leq 0$ that along with the non-negativity constraint $p_{ij} \geq 0$ yields $p_{ij} = 0$ and satisfies the assumption Equation 6.26. When $c_{ij} = 1$, Equation 6.27 is reduced to the redundant constraint $p_{ij} \leq P_{\mathrm{BS}}$, because we have the following equation to assure that the total allocated power to all subcarriers in each time slot is limited by P_{BS}:

$$\sum_{i=1}^{U} \sum_{j=1}^{K} c_{ij} p_{ij} \leq P_{\mathrm{BS}}. \tag{6.28}$$

In the presence of the set of Equation 6.27, that guarantees the restriction Equation 6.26, the variables c_{ij} can be removed from the Equation 6.28 as follows:

$$\sum_{i=1}^{U} \sum_{j=1}^{K} p_{ij} \leq P_{\mathrm{BS}}.$$

The transmission rate to each user depends on the number and index of allocated subcarriers to the user and allocated power to each subcarrier. If continuous rate adaptation is assumed, the approximate rate of the ith user, r_i, can be obtained by either Equation 6.18 or Equation 6.23 as follows:

$$r_i = \sum_{j=1}^{K} r_j \quad \text{bits/s/Hz}. \tag{6.29}$$

The heterogeneous traffic in the network inquires different QoS. The minimum service rate requirement of the ith user, $R^i_{\min}$, is guaranteed through the following equation:

$$r_i \geq R^i_{\min} \quad \forall i \in \mathcal{U}.$$

Respecting the equation listed above and the chosen objective function, $F_i(r_i)$, for user i, the resource allocation optimization problem can be modeled as follows:

$$(P_1) : \max_{c_{ij}, p_{ij}} \sum_{i=1}^{U} F_i(r_i) \tag{6.30}$$

$$\text{s.t.} \quad r_i = \sum_{j=1}^{K} r_{ij} \qquad \forall i \in \mathcal{U}, \tag{6.31}$$

$$r_i \geq R^i_{\min} \qquad \forall i \in \mathcal{U}, \tag{6.32}$$

$$\sum_{i=1}^{U} \sum_{j=1}^{K} p_{ij} \leq P_{\text{BS}}, \tag{6.33}$$

$$\sum_{i=1}^{U} c_{ij} \leq 1 \qquad \forall j \in \mathcal{K}, \tag{6.34}$$

$$0 \leq p_{ij} \leq P_{\text{BS}} c_{ij} \qquad \forall i \in \mathcal{U},\ \forall j \in \mathcal{K}, \tag{6.35}$$

$$c_{ij} \in \{0, 1\} \qquad \forall i \in \mathcal{U},\ \forall j \in \mathcal{K}. \tag{6.36}$$

Problems (P_1) is an MINLP problem. Solving MINLP problems can be very challenging, due to the combination of mixed integer and nonlinear program difficulties in MINLP problems [27]. It is proved in Ref. [28] that the integer variables in problem (P_1) are redundant and can be eliminated. Accordingly, a nonlinear programming (NLP) model is proposed that unifies the subcarrier and power allocation in a rate allocation problem. Equation 6.34, defined below, is replaced by Equation 6.37 for this purpose. For every $\hat{i} \in \mathcal{U}$ and for every $j \in \mathcal{K}$:

$$r_{\hat{i}j} \cdot r_{ij} = 0 \qquad \forall j \in \mathcal{K}, \forall i \in \mathcal{U}, \forall \hat{i} \in \mathcal{U}, i \neq \hat{i} \tag{6.37}$$

It is proved that Equation 6.37, the same as Equation 6.34, guarantees exclusive rate allocation to the ith user on the jth subcarrier and the optimal value of problem (P_1) equals the optimal value of problem (P_2) stated as follows [28].

$$\begin{aligned}
(P_2) : \quad & \max_{r_{ij}} \sum_{i=1}^{U} F_i(r_i) \\
\text{s.t.} \quad & r_i = \sum_{j=1}^{K} r_{ij} && \forall i \in \mathcal{U}, \\
& r_i \geq R^i_{\min} && \forall i \in \mathcal{U}, \\
& \sum_{i=1}^{U} \sum_{j=1}^{K} \frac{1}{r_{ij}} (2^{r_{ij}} - 1) \leq P_{\text{BS}}, \\
& r_{\hat{i}j} r_{ij} = 0 && \forall i \in \mathcal{U} \setminus \{\hat{i}\}\ \forall j \in \mathcal{K}, \\
& 0 \leq r_{ij} && \forall i \in \mathcal{U},\ \forall j \in \mathcal{K}.
\end{aligned} \tag{6.38}$$

The new model will be easier to deal with, both by optimal/suboptimal and heuristic approaches. As the objective function is continuous over the range of allocated rates and the feasible region is closed and bounded, the extreme value theorem (Weierstrass Theorem) implies that problem (P_2) has global optimal solution(s). Extreme value theorem: Let f be a continuous real-valued function whose domain, D_f, is bounded and closed. Then, there exist x_1 and x_2 in D_f such that

$$f(x_1) \leq f(x) \leq f(x_2) \quad \forall x \in D_f.$$

In Section 6.3.2, we review several optimal/suboptimal and heuristic solutions proposed in the literature for simple forms of problem (P_1) that relax some constraints and consider linear/concave objective functions. However, none of the literature available schemes includes the total requirement of heterogeneous traffic of WiMAX simultaneously. We justify a utility-based resource allocation, based on (P_2), for WiMAX, discuss the challenges, and apply genetic algorithm to solve the problem and to show the effectiveness of the model.

6.3.2 Related Works

In the following, similar models to (P_1), each with its own definition of objective function and a variation of constraints, are reviewed. We discuss each model in terms of the proposed solution, and practical advantages and disadvantages.

Bit rate maximization problems, maximizing total users' data rate for a given power budget, is the most common objective function deployed in Refs. [20,29–37]. References [29,30] present a framework for the joint subcarrier and power allocation with power constraint modeled as an MINLP problem. Reference [31] formulates the problem by allowing a subcarrier to be shared by multiple users. The optimization problem is decoupled into two subproblems, subcarrier allocation to users and power allocation to subcarriers. A set of users whose transmission on a specific subcarrier maximizes achievable data rate of that subcarrier are determined in subcarrier allocation step. Then, the subcarriers allocated power is determined to maximize the overall data rate. A suboptimal solution in Ref. [32] allocates uniform power to subcarriers. Given the channel gain and the fixed power allocation (P_{BS}/K), the subcarriers rates (r_{ij}) are known. The problem is converted into a linear integer programming (LIP) problem with integer variables c_{ij}. Then, a reduced computational complexity algorithm is deployed to solve LIP by, first, allocating the subcarriers to maximize the total users' data rates, irrespective of the users' minimum required data rate constraint, and, second, adjusting subcarrier allocation to satisfy the constraint of the users' minimum required rate. A more general form of the bit rate maximization problems are weighted rate maximization problems with the objective function max $\sum^U \sum^K \omega_i r_{ij}$. A geometric programming (GP), a special form of convex optimization, has been proposed in Ref. [38] for weighted rate maximization or weighted power minimization. There exist several algorithms to solve GP efficiently and optimally. However, the challenge is to convert or approximate the objective and constraints to be recognized as problems compatible with GP [39].

Unfair rate allocation among users is the major drawback of bit rate maximization problems. The resource allocation is in favor of the users with good channel status. To resolve this issue, Ref. [33] formulates the problem to balance between capacity and fairness. A set of nonlinear constraints are added into the optimization problem to assure proportional users' data rates. The primal solution of the constrained fairness problem is computationally complex to obtain, so a low-complexity suboptimal algorithm that separates subchannel and power allocation is proposed. The decoupled allocation algorithm, first allocates subcarriers assuming uniform power allocation. Then, an optimal power allocation algorithm maximizes the sum capacity while maintaining proportional fairness. Max-min fairness solution is addressed in Ref. [34] by maximizing the minimum users' data rates, i.e., max min r_i. A convex feasible region is obtained for the problem by relaxing the constraint of exclusively allocating one subcarrier to only one user. Assuming equal amount of power is allocated to each subcarrier, Ref. [34] proposes an algorithm to assign subcarriers to the users. Ref. [35] addresses the unfairness issue of OFDMA transmissions and combines the resource allocation problem with a fair scheduling scheme (generalized processor sharing) to compensate for unfairness of bit rate maximization scheme. Also, the principle of generalized processor sharing is deployed as a constraint of the optimization problem in Ref. [20] to allocate the subcarriers fairly among the users.

The definition of the objective function $\sum_{j=1}^{K} c_{ij} r_{ij}$ (bit rate maximization) does not reflect the heterogeneous traffic specification and application requirements. An appropriate form of the objective function in networks with heterogeneous traffic is to maximize aggregate utility functions of all users in the network. A utility function characterizes a user's satisfaction of an application level QoS requirement. A utility function of rate defined as $U(r) = r$ represents that the user's satisfaction increases linearly by allocating more rate to the user, or a step utility function of rate represents that the user expects a threshold rate, allocating less rate is not useful at all, and allocating more rate is wasteful.

Assuming concave or linear utility functions, Ref. [40,41] investigate the utility-based resource allocations in OFDMA networks for both discrete and continuous adaptive rate. The optimization problem is decomposed into two problems: dynamic service addition (DSA) and APA. The DSA problem is modeled as a uniform power allocation problem, and the APA problem is modeled as a fixed subcarrier assignment. Different approaches for solving DSA, APA, and joint DSA/APA problems are proposed. DSA is relaxed to a nonlinear integer (binary) problem. A sorting search algorithm is proposed for subcarrier assignment. When all utility functions are linear or subcarriers bandwidth is small enough to be considered infinitesimal (rate region is concave), sorting search algorithm gives optimal solutions. Otherwise, the solution is suboptimal, but it reduces the computation complexity. A sequential-linear-approximation water-filling algorithm is proposed to solve the APA continuous rate adaptation. The relaxed nonlinear concave problem is approached by a series of linear optimization problems derived by a sequential-linear-approximation algorithm named Frank-Wolfe method. For APA with discrete rate adaptation, a greedy algorithm is deployed to allocate bits and the corresponding power. In each bit loading iteration, the greedy algorithm allocates power to some subcarriers that maximize the utility argument per power. Assuming concave utility functions, the greedy algorithm results in optimal bit loading and power allocation. Finally, a joint DSA and APA solution is proposed for the original problem. For continuous rate adaptation, a combination of iterative subcarrier assignment, power allocation, and the update of marginal utility is deployed. A new subcarrier assignment is derived based on the property of the subgradient property of concave utility function; the corresponding power allocation is determined by linear approximation of the objective function; the algorithm stops when the marginal utility function is negligible. For discrete rate adaptation, a combination of sorting-search DSA and the greedy APA algorithm is deployed.

The suboptimal or heuristic algorithms from previous papers have considered specific scenarios, such as homogeneous traffic or concave objective functions. These assumptions are not valid for modeling heterogeneous services with nonconcave utility functions as in WiMAX. Commonly obtained application level utility functions for real-time and non-real-time traffic are sigmoid and logarithm functions as shown in Figure 6.4. While a logarithm function is concave, sigmoid functions and most of application level utility functions of real-time traffic are not concave. Such utility functions yield maximization problems whose objective functions are not concave. When the set of feasible solutions that satisfy all constraints, also known as feasible region, is a convex set, and the objective function is concave, any local optimum will be a global optimum solution. Moreover, for many concave utility functions the optimization problem can be solved efficiently. In the problem of utility maximization for heterogeneous traffic, some of the utility functions are not concave (and consequently nonlinear), so finding a global optimum is computationally difficult, and the available softwares can only offer a local solution. Search algorithms that span the entire feasible region can obtain the near optimal solutions, but the solution time is not polynomial. We have applied genetic

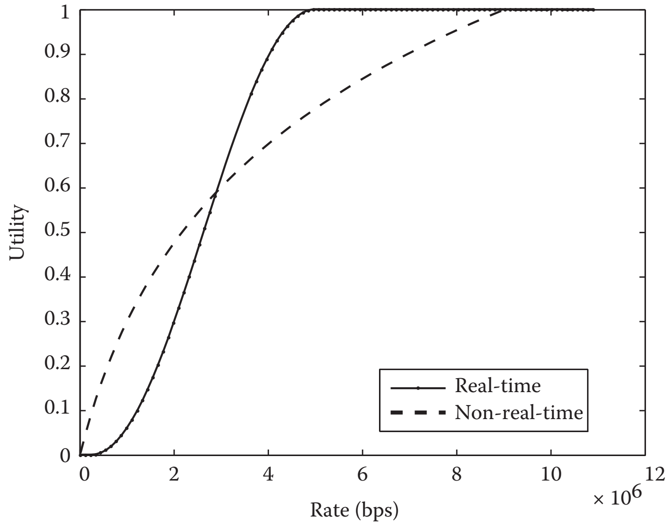

FIGURE 6.4 Typical utility functions for real-time and non-real-time traffic.

algorithm to solve the problem [28]. Simulation results show the genetic algorithm effectiveness in utilizing resources and the convergence of obtained solution.

6.3.3 Uplink Subcarrier and Power Allocation

Although resources are user specific in UL, such as user devices power, users rely on the BS for signaling CSI, and resource allocation in PMP and centralized mesh. In PMP mode, users inform the BS of their CSI in each MAC frame, or average CSI of each user over several MAC frame. In centralized mesh, the nodes send their available resources (in terms of the quality or capacity of their links to their neighbors) and their bandwidth requests to the BS. The BS determines the allocation vector and distributes it to the nodes in PMP and centralized mesh. Similar to DL, an objective function of rate may be maximized to allocate spectrum and power in UL, except the power is constrained by users' specific power limitation. Therefore, only the total power constraint of the BS, $\sum_{i=1}^{U}\sum_{j=1}^{K} p_{ij} \leq P_{\text{BS}}$, is replaced by the power constraint of individual users, $\sum_{j=1}^{K} p_{ij} \leq P_i \quad \forall\, i \in \mathcal{U}$, where P_i is the ith user power constraint.

Due to the limited power of the users' devices, power minimization is a well-considered objective in UL resource allocation problems. The problem of power minimization in UL has the same objective function as the ones in DL, except a weighted power objective function may be used, i.e., $\min \sum^{U}\sum^{K} \lambda_i p_i j$ [38]. In other words, minimizing the total power is an appropriate objective in DL where BS is the only source of power. Users in UL may have diverse power constraint, so a weighted power minimization is more appropriate.

6.4 DECENTRALIZED SUBCARRIER AND POWER ALLOCATION SCHEMES

The distributed infrastructure of WiMAX mesh and relay networks, and the need for reducing communication overhead between the BS and network nodes are the motivations behind proposing decentralized resource allocation schemes. Potentially, either no central controller exists or it does not influence the allocation decision in a decentralized resource allocation. These facts make the decentralized schemes more scalable.

Resource allocation in decentralized networks is essentially different from centralized one. In centralized schemes, the BS collects CSI from all users, allocates the subcarriers or power to the users, and informs the users of allocated resources. On the other hand, users may not need to know the CSI of the other parties in decentralized schemes. Besides, the parties may not be aware of the decision of each other, so a collision is probable. Accordingly, in each proposed distributed resource allocation scheme for OFDM-based networks, the following questions should be answered:

- How does a user achieve the required CSI? The hidden terminal and exposed node problems are common problems in self-organized and decentralized networks, because it is assumed that no central controller exists to assist in signaling. Besides, the signaling overhead should be reasonable for a practical implementation.
- How should the node coordinate or compete with the other nodes to attain the resources? A node does not know the requirements of the other nodes, at each instant, so competence or coordination is a "must" for a node which wants to start capturing the resources.

An interference aware subchannel allocation scheme that overcomes the drawbacks of decentralized schemes, i.e., hidden and exposed node problems is proposed in Ref. [42]. As the scheme uses updated CSI at the beginning of each MAC frame, the channel does not need to be assumed time-invariant over multiple MAC frames. The scheme is appropriate for OFDM-TDD networks. The MAC frame is divided into mini-slots; at the first mini-slot of each MAC frame the ongoing receiver nodes broadcast a busy signal to inform the respected transmitters of the quality of the allocated subchannel. The inactive nodes does not send any busy signal. The ongoing transmitter nodes listen to the busy signal and adapt their subcarrier allocation to their specific receiver nodes according to the information on the busy signal. Also, a node that wants to start transmission listens to the busy signal and chooses the subcarriers that are not interfered by ongoing transmissions and their interference. In other words, it selects those subcarriers with a received busy signal power less than a threshold. The advantages of the scheme are as follows:

- Signaling overhead is low compared to other radio resource allocation schemes
- The co channel interference is reduced significantly since the scheme is interference aware
- Full frequency reuse is possible

A decentralized power allocation problem for a cooperative transmission is formulated in Ref. [43]. The objective is to minimize the total transmission power of all users subject to providing minimum rate requirement of each user. The network model uses a time division multiple access with the OFDM multiplexing (TDMA-OFDM), so only one user accesses the total OFDM subcarriers in each time slot. The user may allocate some of the subcarriers to transmit its traffic and the rest of subcarriers to relay the other users' traffic to minimize total transmission power. In other words, the resource allocation problem determines if a user should cooperate with other users, and in case of cooperation it determines the subcarriers and power allocation. A cooperative user may be allocated more power than a non cooperative user, because its location and channel gain allows it to cooperate with other users. However, the total network power is minimized by cooperation among users. A decoupled subcarrier and power allocation scheme is proposed to solve the problem.

Assuming an access point in the network, Ref. [44] proposes a distributed decision-making scheme for the resource allocation. Each user measures its CSI upon receiving a beacon signal from the access point. The subcarriers are divided into several groups (equal to the number of users), and the approximate channel gain of each group for each user is estimated. Then, the users contend with each other to achieve the group with the best channel quality of their own. A backoff mechanism is proposed to avoid collision. Each user start contending for the best group of subcarriers after a backoff time which is proportional to the best group gain for that user. After contention, the access point informs the users of the winners which can transmit in the next transmission interval. A frame is divided into three subframes, contention, acknowledge, and transmission subframes. This scheme is actually a distributed resource allocation scheme for a centralized network that aims to reduce the signaling overhead and processing task of the access point.

A collaborative subcarrier allocation using the swarm intelligent is proposed in Ref. [45]. The scheme relies on the central controller to achieve the updated information of available subcarriers and the highest and lowest demands for each subcarrier. In other words, the nodes negotiate with the central controller iteratively in a negotiation phase. In each iteration, the nodes inform the central controller of their demand for a specific subcarrier. Then, the central controller broadcast a message indicating the highest and lowest demands for each subcarrier. Based on the feedback messages that occur several times in each negotiation phase, the nodes intelligently decide upon subcarriers.

A comparison between the capacity performance of OFDM-TDMA and OFDM-FDMA in a two-hop distributed network is performed in Ref. [46]. The time frame is divided by two in OFDM-TDMA. In each half of the time frame, all subcarriers are devoted for transmission over one hop. A power allocation algorithm is proposed to maximize the end-to-end capacity subject to the overall transmit power constraint of the two hops. For OFDM-FDMA, the subcarriers are assigned to the two hops without overlapping and a joint subcarrier and power allocation algorithm is proposed. The simulation performance results of the algorithms show that OFDM-FDMA achieves a higher end-to-end capacity than OFDM-TDMA.

6.5 OPEN RESEARCH CHALLENGES

Although the resource allocation for OFDM-based networks has been well studied in the literature, few schemes have been specifically designed for WiMAX. These schemes should be modified or new schemes should be defined for OFDM-based WiMAX to effectively utilize the network resources and improve the network performance for integrated voice, video, and data services over fixed, nomadic, portable, and fully mobile users. An appropriate resource allocation scheme for OFDM-based WiMAX should consider diverse QoS requirement of heterogeneous traffic and mobility issues simultaneously, because a scheme that guarantees QoS for one type of traffic in a fixed network may not perform well for a different type of traffic in a fully mobile network. Moreover, the scheme should balance between users requirements and service providers revenue.

The proposed scheme should carefully consider channel characteristics; ignoring some channel characteristic to make resource allocation easier may result in an impractical scheme, e.g., interference may be a strict constraint in a distributed scheme. A signaling mechanism for reporting CSI and allocation vectors among correspondent nodes, such as the BS and users, should be identified. The CSI measurement may cause an unacceptable overhead when a large number of clients exist. It is usually assumed that perfect CSI is achievable for all users at the same time and at regular intervals, while the wireless channel impairment can make this assumption totally impractical [47]. Overall, a resource allocation scheme should be robust to imperfect CSI and balance between performance gain achieved by network adaptivity and performance loss due to network complexity.

6.6 CONCLUSION

The main objective of this chapter is to investigate the resource allocation schemes for WiMAX networks that adopt OFDM and OFDMA as their multicarrier transmission technologies. We investigate how a resource allocation scheme can take advantage of the OFDM technique flexibility in terms of subcarrier and power allocation to assign resources to achieve a specific objective. We categorize the schemes based on centralized, where a central controller allocates resources, and decentralized, where the users coordinate or compete to achieve resources. Variants of a classical model for centralized resource allocation schemes are reviewed, and an appropriate scheme for OFDM-based WiMAX networks that conforms the IEEE 802.16 standard and its diverse service flows is proposed.

The reviewed decentralized resource allocation schemes outline the basic objectives and challenges of the OFDM resource allocation schemes when the central node is not available or users are coordinate or compete to share the available resources.

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AQ1 Both "D" and "d" has been used in the subscript for Doppler effect. Please make one form consistent, if appropriate.
AQ2 Please provide the expansions for MAC, RMS, IFFT/FFT, AWGM, and APA, if appropriate.
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